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OPTIMIZING THE HEAT PIPE FOR OPERATION IN A MAGNETIC FIELD WHEN LIQUID METAL WORKING FLUIDS ARE USED

R. W. Werner

M. A. Hoffman

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Lawrence Livermore Laboratory

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Abstract

A novel method for reducing the magnetohydrodynamic (MHD) pressure drops in the liquid metal flow in a heat pipe wick is described. By flattening the heat pipe, the eddy current return path in the metallic heat pipe wall is increased significantly, thereby increasing the effective wall resistance. This, in turn, reduces the magnitude of the MHD pressure drop. The same principle can also be applied to flows of liquid metal coolants in a magnetic field.

OPTIMIZING THE HEAT PIPE FOR OPERATION IN A MAGNETIC FIELD WHEN LIQUID METAL WORKING FLUIDS ARE USED

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To better adapt the heat pipe to the conditions of operation in a magnetic field, several important modifications can be made to its structural shape and the arrangement of liquid and vapor flow passages. The evolution of a new heat pipe design for operation in strong magnetic fields is described in this patent disclosure.

In a classical heat pipe, evidenced as a long tubular structure where the length $\ell >>$ tube diameter, d, and the wicking structure is a screen-like material laid up against the inner wall of the tube, the pressure drop in the liquid flow is determined by r_c, the pore size of the capillary wick. That is to say, the liquid flow channel geometry is the same as the capillary wick geometry. A small value of r_c is very critical for good capillary pumping. This is illustrated in the following equation for a classical heat pipe operating in a magnetic field in the gravity-assisted mode[1]:

$$\Delta P_C + \Delta P_G \geq \Delta P_V + \Delta P_\ell + \Delta P_M$$

Pressure Rise due to Capillary Forces	+	Pressure Rise due to Gravity	$\geq$	Pressure Drop in Vapor Flow	+	Pressure Drop in Liquid due to Viscous Forces	+	Pressure Drop in Liquid due to Magnetic Field

For a high-performance , liquid metal heat pipe in the inertia flow regime, the approximate pressure drop expressions are:

$$\frac{2\gamma\cos\theta}{r_c} + \rho_\ell g \ell \sin\phi \geq \frac{\left(1 - \frac{4}{\pi^2}\right) Q^2}{8\rho_v r_v{}^4 L^2}$$

$$+ \frac{b\eta_\ell Q\ell'}{2\pi\left(r_w{}^2 - r_v{}^2\right)\rho_\ell e\cdot r_h{}^2 L}$$

$$+ \left(H + \frac{H^2 C}{1 + C}\right)\frac{\eta_\ell Q\ell'}{2\pi\rho_\ell\left(r_w{}^2 - r_v{}^2\right)w_{\|}{}^2 L\cdot e}$$

If the classical heat pipe geometry is used, the dimension r_c plays a dual role since $r_c = r_h = w_{\|}$. First in order to provide maximum capillary pumping, we would like to make the value of r_c a minimum. However, as r_c is decreased, the effect is to increase the viscous drag in the liquid in inverse proportion to r_c^2. The magnetic pressure drop is also adversely affected, primarily through the effective wall conductance ratio $C \approx \sigma_w t_w/\sigma_\ell w_{\|}$, when metallic wicks and walls are used.

It is important to recognize that the only place r_c must be retained for capillary pumping is at the interface between liquid and vapor. Therefore, in the liquid flow region leading to the capillary, the dimensions of the flow channel can be independent of r_c and can take on whatever values produce the best heat pipe. This observation has already been made by others, and one of the proposed geometries is the channelled heat pipe where slots are provided for liquid flow and the screen or wick now lies on top of the channel dividers (for example, see Ref. [2]). The characterizing dimension in a channelled heat pipe for the liquid pressure drops now becomes $2w_{||}$ of the small channels, as shown on the attached figure, while r_c of the screen still governs the capillary pumping pressure term. When the size and location of these liquid channels were optimized so as to minimize detrimental effects from the magnetic field, substantial improvement in performance in a magnetic field was predicted for a channelled heat pipe[3].

Recently Hoffman and Werner, in investigating further possible improvements (particularly for the B field effects), first determined that improvements were potentially possible by substituting a clear, unobstructed annular space in place of the individual channels within the annulus. The idea of using an annular liquid return channel was investigated many years ago to help reduce the ordinary liquid viscous pressure drop (for example, see Refs. [4], [5]). In the presence of a magnetic field, the effect of the unobstructed annulus can be even more dramatic. The critical dimension, $2w_{||}$, in the magnetic pressure drop term which we wish to maximize increases significantly. It is estimated to be on the order of $\pi d/4$ in the top and bottom regions of the round heat pipe (see the attached figure). However, the magnetic field would still severely retard the liquid flow in the side regions where the effective $2w_{||}$ is still small. Unfortunately, these side regions cannot simply be eliminated when the heat pipe is used in applications where there is heating all around the perimeter.

Using this as a starting point and recognizing further that the important dimension in the magnetic pressure drop was $w_{||}$, a new, striking improvement became possible by Hoffman's observation that if the round tube were flattened, the flattening process would cause $w_{||}$ to become very large and would virtually eliminate the side regions (see figure).

The important magnetic pressure drop term now becomes:

$$\left(-\frac{dp}{dx}\right)_M = \left(H + \frac{H^2 C'}{1 + C'}\right) \frac{\eta_\ell \bar{u}}{w_{||}^2} \qquad \text{(for } H > 10\text{)}$$

where $H \equiv w_{||} B \sqrt{\dfrac{\sigma_\ell}{\eta_\ell}}$

and where C' can be less than the classical C defined as:

$$C \equiv \frac{\sigma_w t_w}{\sigma_\ell w_{||}}$$

For small C', $\dfrac{C'}{1 + C'} \rightarrow C'$

$$\therefore \left(-\frac{dp}{dx}\right)_M \simeq \left[\frac{B_\perp}{w_{||}} \sqrt{\frac{\sigma_\ell}{\eta_\ell}} + B^2 \left(\frac{\sigma_\ell}{\eta_\ell}\right) x\ C'\right] \eta_\ell \bar{u}$$

The effective wall conductance ratio, C', is a complex function of the geometry and electrical conductivities of the wall and screen material and the liquid metal working fluid for the flat heat pipe. Preliminary estimates indicate that for the case where $C\sqrt{H} > 1$, C' may be as low as the following:

$$C' \approx (\text{constant}) \times C \frac{w_\perp}{w_{||}}$$

where the constant is on the order of 2 to 3.

For the case where $C\sqrt{H} \ll 1$, preliminary estimates indicate that C' may approach the following low value:

$$C' \rightarrow (\text{constant}) \times \frac{w_\perp}{w_{||}\sqrt{H}}$$

where the constant here is on the order of 3 to 4. In both cases, C' can be made much less than the classical C by making $w_{||} \gg w_\perp$.

The progression of improvements is shown in summary form on the attached figure. This constitutes a disclosure of a new idea for an improved heat pipe and forms the basis for a patent application in the joint names of Myron A. Hoffman and Richard W. Werner

Nomenclature

γ = surface tension, N/m

ρ_ℓ = liquid density, kg/m^3

ρ_v = vapor density, kg/m^3

g = gravity term, m/s^2

r_c = capillary radius, m

ℓ = heat pipe length, m

ℓ' = effective length, m

θ = contact angle of the liquid meniscus

ϕ = angle of inclination from horizontal

Q = energy flow, axial, W

L = latent heat of vaporization, J/kg

η_ℓ = liquid viscosity, Ns/m^2

$\overline{u}$ = average velocity, m/s

$w_\parallel$ = half channel width parallel to magnetic field, m

$w_\perp$ = half channel width perpendicular to magnetic field, m

B = magnetic field, Tesla

σ_ℓ = electrical conductivity of fluid, mhos/m

σ_w = electrical conductivity of tube wall, mhos/m

H = Hartmann number

C = conductance ratio

e = unobstructed liquid flow area fraction

b = constant determined by liquid flow geometry

r_h = half the hydraulic diameter of the liquid flow channel

r_w = inside radius of tube, m

r_v = radius of vapor flow conduct, m

References

1. T. P. Cotter, "Theory of Heat Pipes," Los Alamos Scientific Laboratory Report LA-3246-MS, February 1965.

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4. J. E. Kemme, "Ultimate Heat Pipe Performance," IEEE Transactions on Electron Devices, Vol. ED-16, No. 8, August 1969, pp. 717-723.

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Optimizing the Heat Pipe
Shape for High Performance in a Magnetic Field

- Objective: To increase $2w_{\parallel}$ so as to decrease the magnetic pressure drop.
- Two important modifications made to heat pipe shape:
    - Use an unobstructed annulus for liquid flow instead of a series of grooves.
    - Depart from the conventional tube shape and use a flattened tube.
- The design evolution was as follows: